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Antihydrogen is the antimatter equivalent of the hydrogen atom. It is of fundamental interest for, among other things, tests of CPT symmetry and measurements of gravitational effects on antimatter. In 2002 the ATHENA experiment succeeded both in synthesizing cold antihydrogen atoms from trapped plasmas of positrons and antiprotons, and in detecting the annihilation of the anti-atoms when they escaped the apparatus. In this colloquium I will describe the ATHENA experiment and the developments that resulted in this success. I will also discuss subsequent experiments aimed at understanding the physics of antihydrogen production, and the future of antihydrogen physics will be addressed.

ref: M. Amoretti et al., Nature **419**, 456 (2002)

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Abstract not available at time of publication.

Guiding Center Drift Atoms

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The ATRAP and ATHENA collaborations at CERN have both reported the production of weakly bound antihydrogen atoms. Although these atoms are often referred to as high-n Rydberg atoms, the strong magnetic field in which they reside makes them very different from a Rydberg atom with a Kepler orbit. More properly these weakly bound and strongly magnetized systems should be referred to as guiding center drift atoms [1]. The cyclotron frequency for the positron is sufficiently large and the cyclotron radius sufficiently small that the positron dynamics can be treated by guiding center drift theory. The type of motion executed by the $\bar{e} - \bar{p}$ system depends on the relative size of various dimensionless parameters. In a particularly simple limit, the guiding center for the positron oscillates back and forth along the magnetic field in the Coulomb well of the antiproton, and more slowly $\mathbf{E} \times \mathbf{B}$ drifts around the antiproton. The pair moves across the magnetic field with the initial ion velocity like a neutral atom. In another limit, the positron and antiproton $\mathbf{E} \times \mathbf{B}$ drift together across the magnetic field. In a third limit, the antiproton executes a large cyclotron orbit in the vicinity of the positron, which is effectively pinned to the magnetic field. This paper will analyze and classify the possible motions. The dynamics is integrable when the cyclotron action and the action for the field aligned oscillatory motion are good adiabatic invariants. The atomic states are quasi-classical, so quantum numbers are easily assigned using the Bohr-Sommerfeld rules.

This work is supported by National Science Foundation grant PHY-9876999.

[1] M.E. Glinsky and T.M. O'Neil, "Guiding Center Atoms: Three-Body Recombination in a Strongly Magnetized Plasma," Phys. Fluids B **3**, 1279-1293 (1991).

"Three dimensional imaging of trapped antiprotons"

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We demonstrate three dimensional imaging of antiprotons in a Penning trap. Antiprotons, upon annihilation, produce several charged particles, and we reconstruct the annihilation vertices from the trajectories of the charged tracks, measured by a silicon microstrip detector. Our antiproton imaging has unique sensitivity to the particle loss processes. This allowed us to observe directly the spatial, as well as temporal, distributions of the particle loss in a trap. Among our findings are (1) the radial loss of antiprotons on the electrode wall is localized to small spots, strongly breaking azimuthal asymmetry expected for an ideal trap, (2) the number of the these spots grows with the number of the electrodes used to trap antiprotons.

The advantages and the limitations of our imaging method for plasma diagnosis will be described, and the implications of antiproton imaging for antihydrogen detection will be discussed.

Trap-Based Positron Beams*

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A review of trap-based positron beams including current and potential applications will be presented. Positron traps have the capability for producing high-quality positron beams and intense positron pulses for a variety of scientific and technological applications [1]. Trap-based beams offer unique advantages over conventional positron beams with respect to important beam parameters. For example, positron beams with energy spreads as low as 18 meV have been created [2] and even colder beams are possible. Techniques for accumulating positrons in traps and manipulating them before release will be described, including cooling, compressing, and bunching techniques [4]. The extraction of beams from the magnetic field of the trap and the limits on beam brightness and focusing will be discussed. Applications for cold positron beams described will include the study of positron-atom and positron-molecule interactions [3], mass spectrometry, and positron probes for materials science [1]. Positron traps also have the potential for creating intense positron pulses for a range of scientific applications including the creation of positronium molecules [i.e., $(e^+e^-)_2$], Bose-Einstein condensation of positronium atoms, a positron annihilation gamma-ray laser [5], and the measurement of anomalous electron transport in tokamaks. The future of positron trapping, such as the potential for portable positron traps and the ultimate limits of positron storage, will also be discussed.

*Supported by the Office of Naval Research and the National Science Foundation

1. R.G. Greaves, S.J. Gilbert, and C.M. Surko, *Applied Surface Science* **194**, 56 (2002).
2. S.J. Gilbert *et al.*, *Appl. Phys. Lett*. **70**, 1944 (1997).
3. J.P. Sullivan *et al.*, *Physical Review A* **66**, 042708/1-12 (2002).
4. R.G. Greaves and C. M. Surko, *Phys. Rev. Lett*. **85**, 1883 (2000).
5. A.P. Mills, Jr., *Nucl. Instrum. Methods B* 192, 107-16 (2002).

Abstract Submitted
for the 2003 Workshop on Nonneutral Plasmas

Kinetic Theory for Antihydrogen Recombination Schemes[1] RONALD STOWELL, RONALD C. DAVIDSON, Princeton Plasma Physics Laboratory — Guiding-center kinetic theory has been developed for antihydrogen recombination experiments, which are conducted with magnetic fields of 3 - 5 T; temperatures of 4 - 10 K; positron densities of 10^7 - $10^8\,\mathrm{cm}^{-3}$; and antiproton densities of 10^4 - $2\times10^7\,\mathrm{cm}^{-3}$. Collision operators provide the leading-order correction to weak-coupling theory as the coupling parameter increases. Six collision operators – three Landau analogs and three Balescu-Guernsey-Lenard analogs – are found for particles of unlike charges. One operator is the multiple-species generalization of Dubin's and O'Neil's operator.[2] A stability analysis is performed for counter-streaming positrons and antiprotons occupying a cylindrical region coaxial with an outer conducting cylinder in a constant, axial, magnetic field. The finite transverse geometry of the system is included, leading to a three-dimensional Penrose criterion, which is applied to drifting Maxwellian distributions to obtain the regime of stability as a function of the species' temperature ratio, density ratio and relative mean velocity. Collisional corrections are considered. Terms resulting from collisions between particles of the same species cancel under general assumptions satisfied by both O'Neil's operator[3] and Dubin's and O'Neil's operator.[2] The multiple-species generalization of Dubin's and O'Neil's operator is used for unlike-species collisions to find a collisionally corrected dispersion relation, which is applied to a detailed study of stability.

[1] Research supported by the United States Department of Energy, and in part by the Office of Naval Research.

[2] D. H. E. Dubin and T. M. O'Neil, *PRL* 78(20):3868, '97. The operator is implicit in equation (8).

[3] T. M. O'Neil, *Phys. Fluids* 26(8):2128, '83. See equation (34).

* Oral presentation requested.

Cryogenic, High-field Trap for Positron Storage and Cold Beams*

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A new Penning-Malmberg trap using a 5 Tesla magnetic field and a cryogenic electrode structure (T~10K) has been constructed with the goal of producing large ($N \geq 10^{10}$), high-density positron plasmas and cold positron beams ($\Delta\varepsilon \sim 1$ meV). With background pressures $\leq 10^{-11}$ torr and rotating electric fields to counteract plasma expansion due to background asymmetries, this trap is designed to be a nearly ideal reservoir of positrons with very long confinement and annihilation times. This paper describes recent experiments using electron plasmas to optimize confinement, plasma compression, and extracted beams.

For positron storage, physics issues include optimizing rotating wall compression while balancing expansion heating with cyclotron cooling for plasmas with large particle numbers ($N \leq 10^{10}$). The cold beam and positron storage applications appear to favor different operating regimes, and so it is of interest to determine the dominant transport mechanisms for a relatively wide range of plasma densities, ($n \leq 10^{11}$ cm^{-3}) at temperatures from 1 meV to a few eV. This is a parameter regime that has yet to be fully explored. This trap will be an excellent test bed in which to study the possibility of confining very large numbers of positrons (e.g., $N > 10^{12}$) in a recently proposed multicell geometry [1].

Cold, low-energy positron beams can be extracted from the trap by decreasing the confinement potential. Since the energy resolution of the beam is determined by the plasma temperature, beams with energy spreads ~ 1 meV should be possible. For plasmas with appreciable space charge, beams with very small diameters ($D \leq 4\lambda_D$) are possible. For example, for $n \sim 10^{10}$ cm^{-3} and $T \sim 10^{-2}$ eV, beam widths of less than 10 μm should be possible.

Specific topics to be discussed include nonequilibrium, 2D radial density profiles in the presence of rotating wall compression and the extraction of beams with diameters comparable to the theoretical limit for this process. First experiments with positrons are scheduled for later this summer.

* Work supported by the Office of Naval Research.
+ In collaboration with Pit Schmidt, James Sullivan and Cliff Surko.

1. C. M. Surko and R. G. Greaves, Radiation Physics and Chemistry, in press; and C. M. Surko, R. G. Greaves, J. R. Danielson and P. Schmidt, this conference.